Consensus-Based and Network Control of UAVs

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Abstract - *During the past few years, research in the field of cooperative control of swarm of robots and specially UAV has continuously increased. In order to develop research in the field of swarm of UAV this paper identifies three problems: the development of a testbed for UAV, the implementation of an ad hoc network and a protocol based on network control, and a consensus control algorithm for cooperative control of UAV. The testbed currently enables us to perform waypoint navigation using a global positioning system (GPS). The protocol communication designed for the ad hoc network has proved to be reliable for our application and can be expanded to be used with different number of agents. The algorithm of consensus control has been analyzed and tested in simulation. Future work will allow implementing the consensus control as centralized control or distributed control.*

Keywords: Consensus Control, Network Control, UAV, Swarm.

1 Introduction

Tasks of aerial reconnaissance and surveillance were not long ago performed exclusively by airplanes under control of a pilot. These tasks were too trivial or dangerous for the pilot's life. The solution to this situation was the development of Unmanned Aerial Vehicles (UAV). The advantages of a UAV include: the life of the pilot is no longer in danger, the autopilot is able to perform waypoint navigation, and sensors and cameras help to perform surveillance and reconnaissance. New developments in the fields of control and communication allowed many researchers the development of algorithms inspired by nature [1]. Many of these efforts were focused in developing algorithms to control not only a robot but a group of robots. A swarm of robots presents interesting challenges. Algorithms of centralized and decentralized control can be applied. In both scenarios, communication is very important, and an ad hoc network needs to be implemented [2]. The application of the idea of a swarm of UAVs presents many challenges but at the same time advantages especially in scenarios where time is a constraint and missions could be performed more efficiently and in less time. Specific applications to UAVs such as formation control [3], flocking [4], and swarming [5] have been developed during the last few years.

1.1 Testbed for a swarm of UAV

The architecture of a system designed to control a swarm of vehicles have had many different approaches. One of them, Cloud Cap Technology Incorporated, designed a base station, pilot console, and operator interface software that provides communication, flight control, telemetry recording, and flight visualization [6]. This system was used by the University of California, [7], Pennsylvania State University [8], and MIT used the system to create a testbed of eight UAVs [9].

1.2 Network Control

Recently, control applications require more precise, robust, and scalable control system; as a consequence, the complexity of control systems has been increased. This includes reliable communication protocols and ways of transmission. Applications of network control, not only in industry but also academic, have been developed in different universities such us the Caltech vehicles used in the DARPA Grand Challenge or the Caltech Multi-Vehicle Wireless Testbed [10].

1.3 Consensus Control

One of the algorithms developed during the last few years is the consensus control based on graph theory. Topics about consensus control were studied by different researchers, many on the field of distributed computation and automation [11]. The cooperation among vehicles to perform a specific task communicating each other was presented in [3]. Many authors developed different approaches and topics related to consensus control. The consensus algorithm can be implemented as a centralized control or decentralized control.

The paper is organized as follows. Section 2 describes the architecture of the proposed system. Section 3 describes the Networked Control approach. Section 4 develops the Consensus Control algorithm and the proposed flight formation algorithm. Section 5 describes the hardware and software implementation of the testbed and presents the results of the waypoint navigation.

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2 Testbed Architecture

2.1 System Architecture

The design approach for the system architecture has been "divide and conquer." The architecture of the system is described in Figure 1.

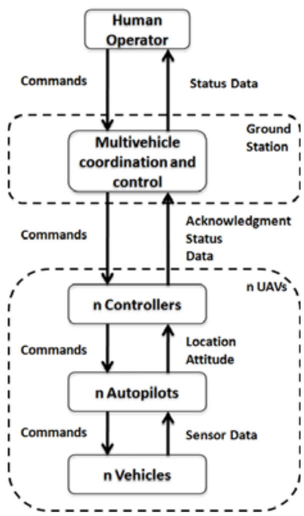


Figure 1. Architecture of the system

The *human operator* (see Figure 1), will provide commands and information to the ground. The *ground station* (see Figure 1) is a personal computer where many of the coordination and control of the swarm will be performed. The architecture of the ground station has been divided in tasks (see Figure 2). The block called *n UAVs* (see Figure 1) represents the robots that the system will be able to control.

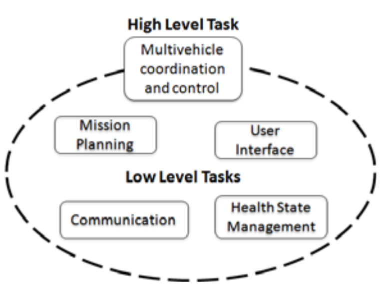


Figure 2. Architecture of the ground station

2.1.1 Multivehicle Coordination and Control

Multivehicle coordination and control is a high level task on the system. Depending on the implemented algorithm, it can be run either on the ground station or the UAVs. If the algorithm runs on the ground station, it will be considered centralized control. On the other hand, if the algorithm runs in every UAV, it will be considered a distributed control. The objective here is to design a testbed where different algorithms and configurations can be tested, more information see [12].

2.1.2 Mission Planning

The mission planning depends on the operator and should be treated as an input to the system. The operator should specify what kind of mission either a UAV or a swarm of UAVs should perform. The system should be able to evaluate based in the UAV information (e.g. position and health state) the most suitable vehicle(s) for the mission. Additionally, the system should be able to optimize the best trajectory in order to save time and energy. The optimization could be approached from the point of view of solving the Traveling Salesman Problem (TSP) [13].

2.1.3 Health State Management

Health state management has been studied by MIT [14]. This task receives special attention because the information provided helps to the mission planning providing information about the health state of every available vehicle. We understand by health state of the vehicle the amount of remaining energy to be operational and if any electronic device is malfunctioning. This block works directly with the mission planning, providing visual information to the operator, and interacting with the algorithms of task assignment and trajectory optimization.

2.1.4 Communication

Communication is a vital component in the system. Without it, we could not be able to coordinate any of the tasks. The system must be able to maintain communication between the ground station and the UAVs. The information received from the UAV will be distributed between the different tasks block of the system. On the other hand, the UAV will receive the task assignment from the ground station. Finally, depending on the swarm control algorithm, the UAVs will be able to coordinate its movements either receiving information from the ground station or the information obtained from the other UAVs.

3 Network Control

Today, different processes or plants are controlled by a single computer. This is possible through the use of the concept of network control. However, the benefit of having a network is considerable, such as faster configuration of controllers. The solution also presents additional problems due to constraints of the network. For example, packets of data can arrive at variable times, not in order or not at all. As a consequence, new control algorithms that overcome these problems have been continuously developed during the past few years, more details see [12].

3.1 Network Control Systems Definition

There are many definitions of Network Control Systems. "Network Control Systems (NCS) are spatially distributed systems in which the communication between sensors, actuators, and controllers occurs through a shared band limited digital communication network" [15], and is complemented by Baillieul and Antsaklis [16] "The universal feature of networked control systems is that the component elements are spatially distributed, may operate in an asynchronous manner, but have their operation coordinated to achieve some overall objective."

3.2 Network Control Structure

The two general configurations in network control systems are direct structure and hierarchical structure. In the NCS direct structure, the advantage of such a configuration is the economy in cabling and remote commissioning of sensors and actuators. In the NCS hierarchical structure, the control network is used to coordinate two or more Level 1 controller by a Level 2 unit [28].

3.3 NCS Hierarchical structure for one UAV

The proposed structure is depicted in Figure 3.. The structure shows at the bottom the plant, represented by the airplane including its sensors and actuators. The Level 1 corresponds to the controller, in our case the autopilot. The autopilot is based on Fuzzy control rules and adaptive control [17]. On top of everything, a Level 2 generates the set points on the PC, more details in [12].

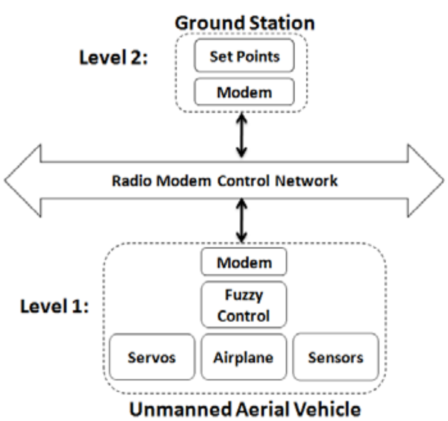


Figure 3. Hierarchical structure of NCS for one UAV

3.4 Communication protocol

In mobile robot design, the way in which the robot will communicate has been always a critical decision. The protocol can be categorized in two types. The first protocol has both electrical and protocol definitions on how the data is transmitted; it is known as the transport layer. The protocol concerned in the actual meaning of the data is also called application protocol or application layer.

3.4.1 Message structure

For the application layer, a protocol based on an ASCII Modbus message is used. Modbus is an application layer protocol based on client/server architecture [18]. Usually, it presents two serial modes: RTU and ASCII. In the project, the ASCII serial frame is used (Figure 4.).

Figure 4. Modbus ASCII serial frame

The message structure used in the application protocol for the project contains the *Address Field* that contains two characters for identification of the UAV. The *Function Code* contains the command to be performed by the receiver. The *Data Field* contains information that is complement for the function code, and the *Error Check* contains the checksum of the string formed by the *Address Field* + *Function Code* + *Data*. A Cyclic Redundancy Check (CRC) method is applied to the message. Table 1 and Table 2 describe the type of message used by the ground station and the UAV to interchange information.

Table 1: Messages sent by the ground station to the UAV

Message send by the Ground Station	**Description**
<a1:do cmd="reqGPS"/>[*checksum*]~	Request information of the UAV current location
<a1:do cmd="reqIMU"/>[*checksum*]~	Request information of the UAV current attitude
<a1:do cmd="GPSdes" lat="xx.xxxxxxxx" lon="xx.xxxxxxxx" alt="xxx.xx"/>[*checksum*] ~	Upload information of the waypoint that the UAV should visit.

Table 2: Messages sent by the UAV to the ground station

Message send by the UAV	**Description**
<a1:info cmd="reqGPS" lat="xx.xxxxx" lon="xx.xxxxx" alt="xxx" bat="xxx"/>[*checksum*]~	Inform the UAV current location and the battery status.
<a1:info cmd="reqIMU" pit=" xx.xxxxx " rol=" xx.xxxxx " yaw=" xx.xxxxx " bat="xxx"/>[*checksum*]~	Inform the UAV attitude and battery status.
<a1:info cmd="GPS_IN"/>[*checksum*]~	Inform a correct reception of the uploaded waypoint.
<a1:info cmd="error"/>[*checksum*]~	Inform an incorrect reception of the uploaded waypoint

4 Consensus control

According Wei, Beard, and Atkins in [19], "Consensus algorithms are designed to be distributed, assuming only neighbor to neighbor interaction between vehicles. Vehicles update the value of their information state based on the information states of their neighbors." Using a consensus law, the objective is to converge to a common value the states of all of the agents in the network. Consensus algorithms have been studied to solve rendezvous problems, formation control problems, flocking, and sensor networks.

4.1 Graph Theory

Figure 5. Swarm of robots with different sensors depicts a group of robots and everyone carries a different type of sensor.

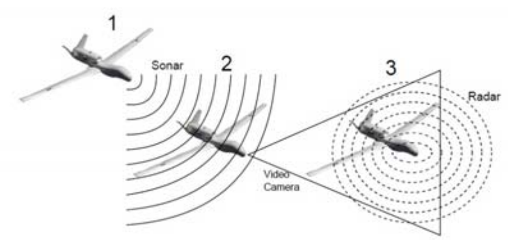


Figure 5. Swarm of robots with different sensors

The formation architecture can be described through the use of graphs (Figure 6.).

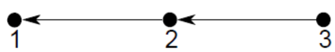
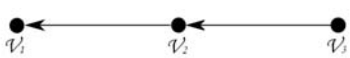


Figure 6. Graph representation of the swarm of robots

A graph $\mathcal{G}$ is a pair $(\mathcal{V}, \mathcal{E})$ where $\mathcal{V} = \{\mathcal{V}_1,\ldots,\mathcal{V}_n\}$7s a finite nonempty *vertex set* and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the *edge set* of ordered pairs of nodes (Figure 7).



$\mathcal{V} = \{\mathcal{V}_1, \mathcal{V}_2, \mathcal{V}_3\}$
$\mathcal{E} = \{(\mathcal{V}_2,\mathcal{V}_1),(\mathcal{V}_3,\mathcal{V}_2)\}$

Figure 7. A graph example

4.2 Rendezvous problem

The rendezvous problem [20] for robots states that: "Given a group of N robots dispersed in a plane, how should they move to gather around a specific location?" Different approaches during the last few years addressed the solution of this problem [21], [22], and [23]. One of them solves the problem using only local information [24] .

The next equation is known as the *consensus equation*.

$$\dot{X}_i = -\gamma \sum_{j \in N_i(t)} (X_i - X_j) \quad (1)$$

Where:

- The robots are planar, $X_i \in \mathbb{R}^2$ i = 1, 2, …, N.
- γ is the weight
- N is the number on agents

4.3 Formation problem

This problem is one of the most common problems in multi-agent control [20]. The problem states that the agents should achieve and maintain a given geometric shape. The next equation describes the consensus equation applied to the formation control.

$$\dot{X}_i = -\sum_{j \in N_i(t)} \left[(X_i - X_j) - (q_{0,i} - q_{0,j}) \right] \quad (2)$$

Where:

$(X_i - X_j)$ should be measured (interagent displacement)

$(q_{0,i} - q_{0,j})$ must be designed apriory

The development of equations (1) and (2) are described in detail in [12].

5 Hardware/software implementation

The testbed has been implemented with the objective to control initially one UAV and perform waypoint navigation. The hardware implementation of the testbed is described in Figure 8..

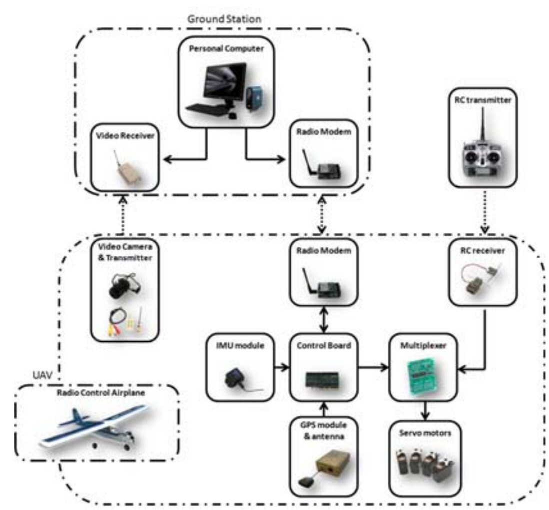


Figure 8. Hardware implementation of the testbed

The ground station is a laptop running Windows XP and Borland Turbo C++ 2006. A program able to control and interact with the UAV has been created. The program can be separated in two parts. The first one is transparent to the user and is where all the algorithms that will control the swarm of UAVs are implemented.

5.1 Simulation results

A simulation of rendezvous and waypoint navigation of a swarm are presented. This paper considers the movement of the UAV in 2 axes. The simulations assume the UAV is able to maintain a predefined altitude using the fuzzy rules and adaptive control developed for the autopilot.

5.1.1 Rendezvous problem

The solution for the rendezvous problem has been simulated in Matlab using the consensus equation (1). Five agents were randomly located on the field. An interaction distance of 0.5 units and coordinate (4,16) for rendezvous were specified. Figure 9 shows the result of the convergence of the vehicles in the x-axis for the coordinate (4,16).

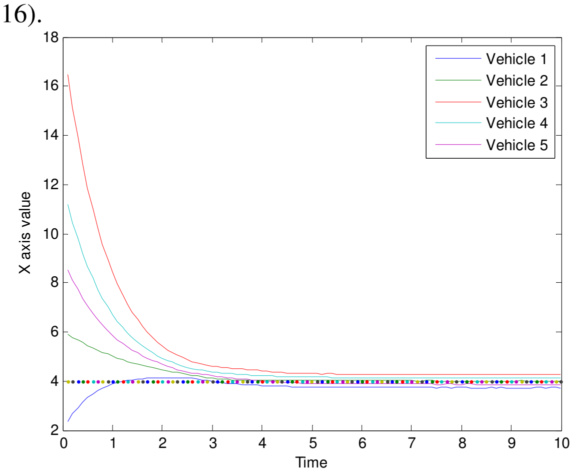


Figure 9. Rendezvous of vehicles around x=4

5.1.2 Formation Problem

The formation problem and the waypoint navigation have been implemented on Matlab using equation (2). The formation has the shape of a circle of radius 1 unit. Figure 10 shows the displacement of the vehicles in the x-axis for waypoints (16,18), (2,4), (18,2), and (4,16).

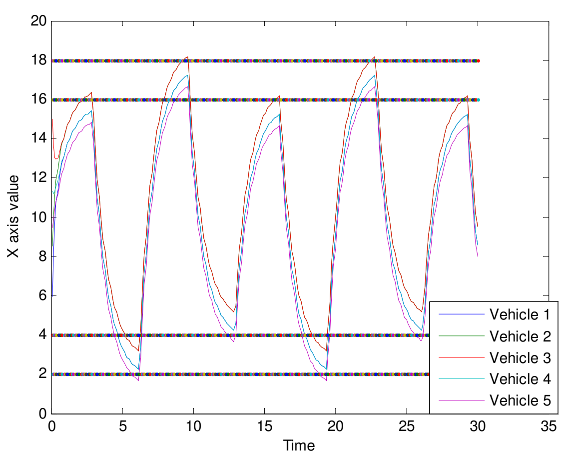


Figure 10. Waypoint navigation of five vehicles in formation

5.1.3 Results of the test flight

The first results of the test flights show the capability of the Gumstix to read the GPS and IMU data from the airplane's sensors. The data collected during flight (Figure 11) was transmitted to the ground station. The proposed communication protocol worked according the tests performed on the ground. Even though, drop of packets occurred during the test, this was not a critical factor, because at this stage the ground station only monitors the UAV behavior. The next test flight will include the waypoint navigation. Communication of waypoint from the ground station to the airplane's computer has been successfully tested on the ground. On the other hand, the fuzzy logic control for the airplane has been tested and is able to maintain the stability of the airplane [17]. For this test, the remote control of the UAV is capable to switch from manual to automatic and vice versa.

Figure 11. Airplane's test flight

6 Conclusions and future work

This project presents a low cost testbed for UAV. The capabilities of sensing and processing installed in the airplane enabled it to be an easily customizable UAV in order to test new control algorithms. The software of the autopilot is easy to program, and customize using C language. The ground station will allow to program specific algorithms according the student requirements. Compared to other testbeds, this one allows us to have complete control of the UAV, and ground station. Network control gives us the support for this type of project, and analyzes the effect of the time delay in the network. According to the simulations, controlling the behavior of the agents using consensus control is possible even when time delay is present in the network. The communication protocol uses the agent name, command, data, and error check. These characteristics allow us to create the logic for the communication protocol. The actual hardware of the UAV allows performing a slow flight due to the airplane characteristics. This is ideal when you need to be more focused in the actual control of the swarm.

The future work will include: image processing of aerial images, development of algorithms based on consensus control for surveillance using a swarm of UAV, and optimization of the communication protocol to allow the use of multiple control stations.

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